MAR 30 1981

MEMORANDUM FOR: File

FROM: M. L. Picklesimer
Fuel Behavior Research Branch

SUBJECT: RELOCATION OF FUEL FRAGMENTS IN BALLOONED FUEL RODS

Neutrographs have shown that pellet fragments are observed to be relocated from other, undeformed sections of the fuel rod to fill up the ballooned section of Zircaloy clad LWR fuel rods burst after in-pile LOCA simulation tests. This has been observed and reported by Karb (Reference 1) in his studies in the FR2 at Kernforschungzentrum Karlsruhe, FRG, and by Yackle (Reference 2) in the LOC-3 and LOC-5 tests in PBF at INEL. Questions have been raised as to when the relocation occurs, to the effects of the fuel fragment relocation on the centerline temperature of the fuel, to the peak surface temperature of the cladding, to the progression of the ballooning of the cladding, and to what account of this observation should be made in LOCA analyses for licensing purposes. This memorandum has been prepared to assemble information pertinent to the provision of an analysis of the problem and answers to the questions raised.

Ex-pile tests of ballooning rods by Wiehr (Reference 3), using internal electrical cartridge heaters in fuel rod simulators and x-ray photography, and Chung, et.al., (Reference 4) using pellet-constrained Joule-heated cladding specimens have shown that once a local plastic instability has formed during ballooning, the remaining deformation required to form the balloon and burst occurs in fractions of a second to a second. Circumferential strains, averaged axially over the ballooned specimens away from the immediate neighborhood of the burst, seldom are higher than 20-25% and should represent the approximate strain present at the time the plastic instability developed. Pertinent figures from their reports are shown in Figures 1 and 2.

Karb (Reference 5) has shown in a special in-pile ballooning test that: (1) the total time of ballooning to large strains over an extended length (approximately 60% strain over 20 cm of length) required no more than 1-2 seconds; (2) fuel relocation must have occurred after the ballooning started; and (3) no significant temperature increases were measured on the cladding, though no thermocouple was located precisely on the ballooned section. Other tests by Karb have shown that the fuel fragmentation was present in the fuel before ballooning and was not caused by the LOCA testing (a companion irradiated, but unballooned, fuel rod had the same particle size distribution as ballooned and burst rods). An excerpt of the data report is presented in Appendix A.

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All of the observations of fuel fragment relocation in ballooned sections of fuel rods have been made on specimens used in experimental in-pile tests examining the behavior of fuel rods in simulated LOCA. In all cases, the ruptured specimens have been subjected to vibration during reflood, removal of the test train from the in-pile tube test apparatus, removal of the specimens from the test trains, transport to the neutrographic facility, and installation in the apparatus for neutrography. Thus, it is not certain when the fuel relocation occurred - during the ballooning, subsequent to the ballooning during reflood, or during handling and transport after the tests were complete. Since the latter cases pose no problem or hazard, and the first could cause increased ballooning strain, it is assumed, for the purposes of this memorandum, that the fuel relocation takes place during ballooning, i.e., the worst case.

Since the fragment sizes are not changed by the LOCA ballooning (see Figure A-3 of Appendix A for companion rods ballooned and unballooned), the relocation is, in effect, a change in the bulk density of the fuel pellets. Though cracked and relocated sufficiently to fill the as-built cladding to pellet gap, the fuel pellet in the unballooned rod section is still at an effective or bulk density nearly identical to its original as-sintered density (nominally 93-95% theoretical). When displaced into the volume of the balloon, the bulk density is decreased significantly, just as is crushed rock formed from bedded layers in a quarry. Handbook values of bulk density for rock, rubble, and gravel formed by crushing large solid bodies range from 0.56 to 0.69 of the original density. Measurements of the ratios of radioisotopic readings on ballooned and unballooned sections of fuel rods from the LOC-3 and LOC-5 PBF tests (Reference 6) give values of about 0.65, which should be proportional to the ratio of the bulk to theoretical densities for the fuel fragments.

Using simple assumptions, a set of calculations have been made to estimate the amount of new fuel entering an axial node of a balloon as a function of the amount of circumferential strain present and the bulk density of the fuel fragments. The values are presented in Table I. These show, for example, that if the bulk density of the fuel fragments is 0.65 theoretical density, then a circumferential cladding strain of more than 24% and a volume increase of more than 54% must be present at a node if any new fuel is to enter that node from other regions. A ballooning strain of 75% is required for the amount of fuel at an axial node of a balloon to be doubled, again for a bulk density of 0.65 theoretical.

Yackle (Reference 6) has performed a set of calculations of centerline and cladding surface temperatures on ballooned fuel rods during LOCA for three levels of cladding circumferential strain, two gases (helium and oxygen), and three levels of fuel fragmentation. The essence of the results are presented in Figure 3 and the complete results in Appendix B. For a circumferential strain of 44%, the cladding temperature rises only about 25 K above that for

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cladding with no strain, while the centerline temperature for the fuel fragments in a ruptured rod increases about 450 K above that for an unstrained rod with no fuel fragmentation. If the circumferential strain is increased to 89%, the cladding temperature is increased about 225 K, while the fuel fragment centerline is increased about 1270 K, both above the conditions for an undeformed rod. To put these strains into perspective, in present day PWR's the cladding of neighboring rods will touch if both balloon coaxially with about 33% circumferential strain, while about 66% strain is required for a ballooning rod to touch an unballooned neighbor. The maximum circumferential strains observed in single rod burst tests with slow heating rates and heated shroud (near adiabatic conditions) range from about 75% to about 90%.

If it can be accepted that the bulk density of fragmented fuel is approximately 0.65 theoretical density, and that no new fuel can enter a ballooning region until space has been made for it to enter at that bulk density, then the circumferential strain in the balloon must exceed 24% before new fuel enters the balloon. Examination of the internal rod pressure curve (P74) in Figure A-2 in the time period between 52 and 58 seconds shows that the major volume increases in the ballooned region of specimen rod E-5 occurred in the 1-1.5 seconds between about 56.5 and 58 seconds elapsed time. It is thought that the ballooned section developed a pin-hole rupture just before 58 seconds which was then covered over by the shroud as the balloon continued to develop (PIE of the specimen is underway). With the termination of the nuclear power, the ballooned section cooled off enough to allow the cladding at the rupture to pull away from the shroud and allow the slow depressurization to proceed. When the system pressure was increased at about 75 seconds (P60), the pressure inside the ballooned rod also increased (P74). It can be argued then that the new fuel enters the ballooned region after the ballooning has occurred and, thus, can not affect the ballooning strains (there isn't time and the strain must be greater than 24% for any new material to enter the local region).

It can be concluded that: (1) the fuel fragmentation reported existed in the fuel rod prior to the LOCA ballooning, (2) the fragmentation was not increased by the LOCA ballooning or thermal shock of quenching, (3) the filling of the balloon at each elevation in the cladding by fuel fragments occurred after the balloon there was formed, (4) the temperature increases to be expected on the cladding due to the insertion of more fuel fragments into the balloon is at most 100 to 200 K even for very large balloons, and (5) the temperature increase to be expected at the centerline in the fragmented fuel is not sufficient to produce melting of the fuel fragments in very large balloons filled with steam, unless the surrounding steam temperature becomes higher than about 1100 K.

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It can also be concluded that the fuel fragment relocation does not produce a problem in the fuel rod during or following the ballooning and bursting. It may, however, constitute a problem of "washout" through the rupture opening during reflood and subsequent flow of coolant to deposit fuel fragments elsewhere in the primary system.

M. L. Picklesimer
Fuel Behavior Research Branch
Division of Reactor Safety Research

Enclosures: As stated

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RECORD NOTE: Drafted and submitted to W. V. Johnston, NRR/CPB on October 8, 1980, acceptance confirmed by D. A. Powers, NRR/CPB on March 23, 1981 by telecon.

MLP GBM

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| NAME | Picklesimer/pr | GPMarino | LHSullivan | | | | |
| DATE | 3/21/81 | 3/27/81 | 3/ /81 | | | | |

## REFERENCES


1. E. Karb, M. Prussmann, L. Sepold, "In-Pile-Experimente zum Brennstabverhalten beim Kühlmittelverluststörfall, Bericht über die Versuchsserie F," KfK 2956, Mai 1980 (Kernforschungzentrum Karlsruhe, FRG).

2. T. R. Yackle, et.al., "An Evaluation of the Thermal-Hydraulic Response and Fuel Rod Thermal and Mechanical Deformation Behavior During PBF Test LOC-3," Proceedings of the ANS Topical Meeting on Thermal Reactor Safety, April 6-9, 1980, Knoxville, Tennessee, USA, Conference-800403, Vol. I, pp. 387-394.

3. K. Wiehr, He. Schmidt, "Out-of-Pile-Versuche zum Aufblähvorgang von Zircaloy-Hüllen Ergebnisse aus Vorversuchen mit verkürzten Brennstabsimulatoren," KfK 2345, October 1977, Gesellschaft für Kernforschung M.B.H., Karlsruhe, FRG.

4. H. M. Chung and T. F. Kassner, "Deformation Characteristics of Zircaloy Cladding in Vacuum and Steam Under Transient-Heating Conditions: Summary Report," NUREG/CR-0344 (ANL-77-31), July 1978, pp. 30-32.

5. E. Karb, "In-Pile Experiments in the FR2 DK-Loop on Fuel Rod Behavior During a LOCA," Presentation to the Workshop on Fuel Behavior, June 1980, Karlsruhe (PNS/NRC/JAERI Annual Information Exchange on Cladding and Codes, Kernforschungzentrum Karlsruhe, Karlsruhe, FRG, June 1980).

6. T. R. Yackle, "Steady State Fuel Rubble Thermal Analysis," HJZ-317-80 correspondence from H. J. Zeile, EG&G, Idaho, to R. E. Tiller, DOE/ID, Idaho Falls, September 29, 1980.

TABLE I

| line | (1) $\varepsilon$ | (2) $\Delta V_{rod}$ | (3) $\rho/\rho_o$ | % New Fuel Added at Axial Node (4) $\rho/\rho_o$=.60 | (5) $\rho/\rho_o$=.65 | (6) $\rho/\rho_o$=.694 |
|---|---|---|---|---|---|---|
| | .10 | .210 | .826 | | | |
| | .155 | .334 | .75 | | | |
| | .20 | .440 | .694 | | | 0 |
| | .24 | .538 | .650 | | 0 | 6.8 |
| | .29 | .667 | .600 | 0 | 8.0 | 15.8 |
| | .336 | .785 | .56 | 7.1 | 16.1 | 23.9 |
| | .400 | .960 | .51 | 17.6 | 27.4 | 36.1 |
| | .414 | 1.000 | .50 | 20.0 | 30.0 | 38.9 |
| | .440 | 1.074 | --- | 24.4 | 34.8 | 44.0 |
| | .500 | 1.250 | --- | 35.0 | 46.3 | 56.2 |
| | .600 | 1.560 | | 53.6 | 66.4 | 77.7 |
| | .75 | 2.063 | | 83.8 | 99.1 | 112.6 |
| | .890 | 2.570 | | 114.2 | 132.1 | 147.8 |

(1) Circumferential strain = $\frac{C-C_o}{C_o} = \varepsilon$

(2) $\Delta V = \frac{V-V_o}{V_o} = \varepsilon^2+2\varepsilon$

(3) Ratio of bulk density of fuel fragment to theoretical density for filling of ballooned volume by only the fuel at the axial node of the calculation

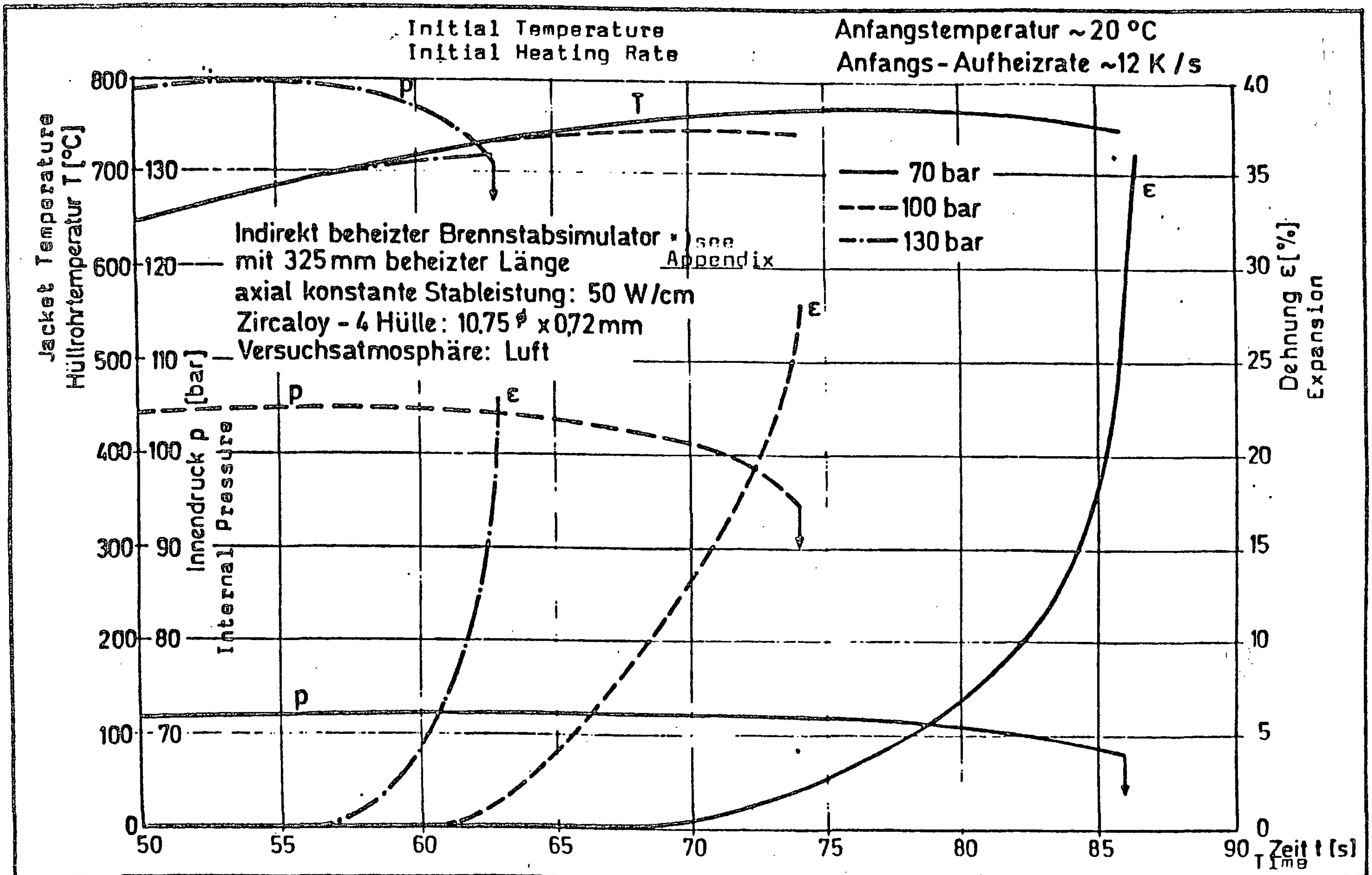
(4), (5), & (6) Per cent new fuel at the axial node required to fill volume of balloon at that node for bulk density ratios of 0.60, 0.65, 0.694

NOTE:

$V = \pi r^2 L \quad c = 2\pi r \quad \pi r^2 = \frac{c^2}{4\pi} \quad \varepsilon = \frac{c-c_o}{c_o}$

$\Delta V = \frac{V-V_o}{V_o}$, $\Delta V = \varepsilon^2+2\varepsilon$

% new fuel = $100 \frac{\rho}{\rho_o} (\Delta V_{rod} - \Delta V_{\rho/\rho_o})$




| GfK - IRB | Ballooning Behavior of a Zircaloy - 4 Jacket<br>Aufblähvorgang einer Zircaloy - 4 Hülle<br>(Meßergebnisse) | Abb. 2 Fig. 2 |
|---|---|---|
| 1975 | | PNS-4238 |

KFK 2345 ( K.Wiehr,H.Schmidt)

FIGURE 1

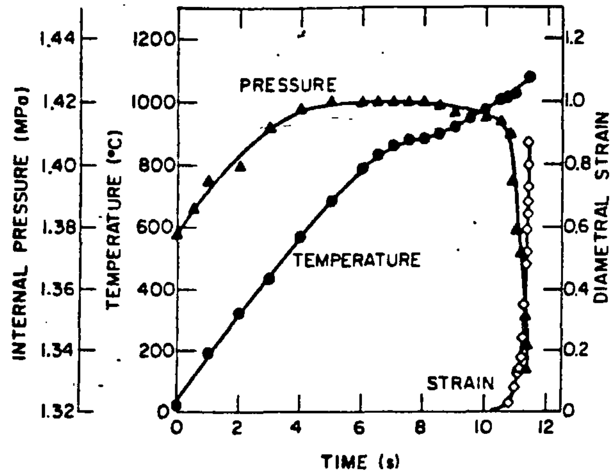



Fig. 8

Temperature, Internal Pressure, Diametral Strain, and Ballooning Profiles as a Function of Time during Rupture Test of Zircaloy Cladding. ANL Neg. No. 306-78-405.

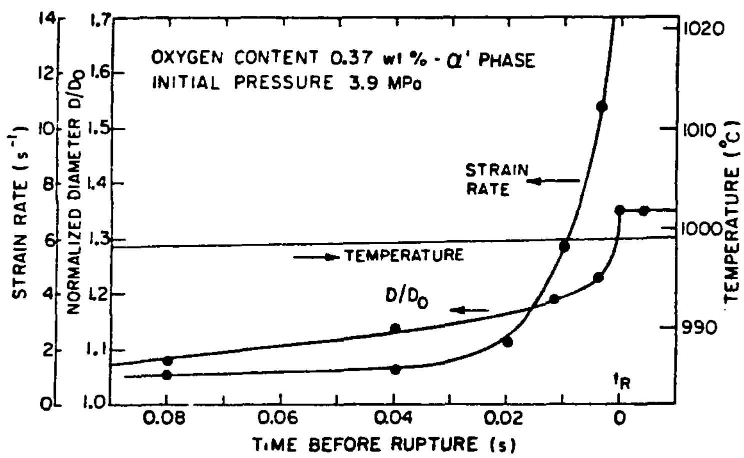



Fig. 9. Diametral Strain, Strain Rate, and Temperature at Burst Region of Zircaloy-4 Specimen Shown in Fig. 7 as a Function of Time near Onset of Plastic Instability. ANL Neg. No. 306-75-204 Rev.


NUREG/CR-0344
ANL-77-31



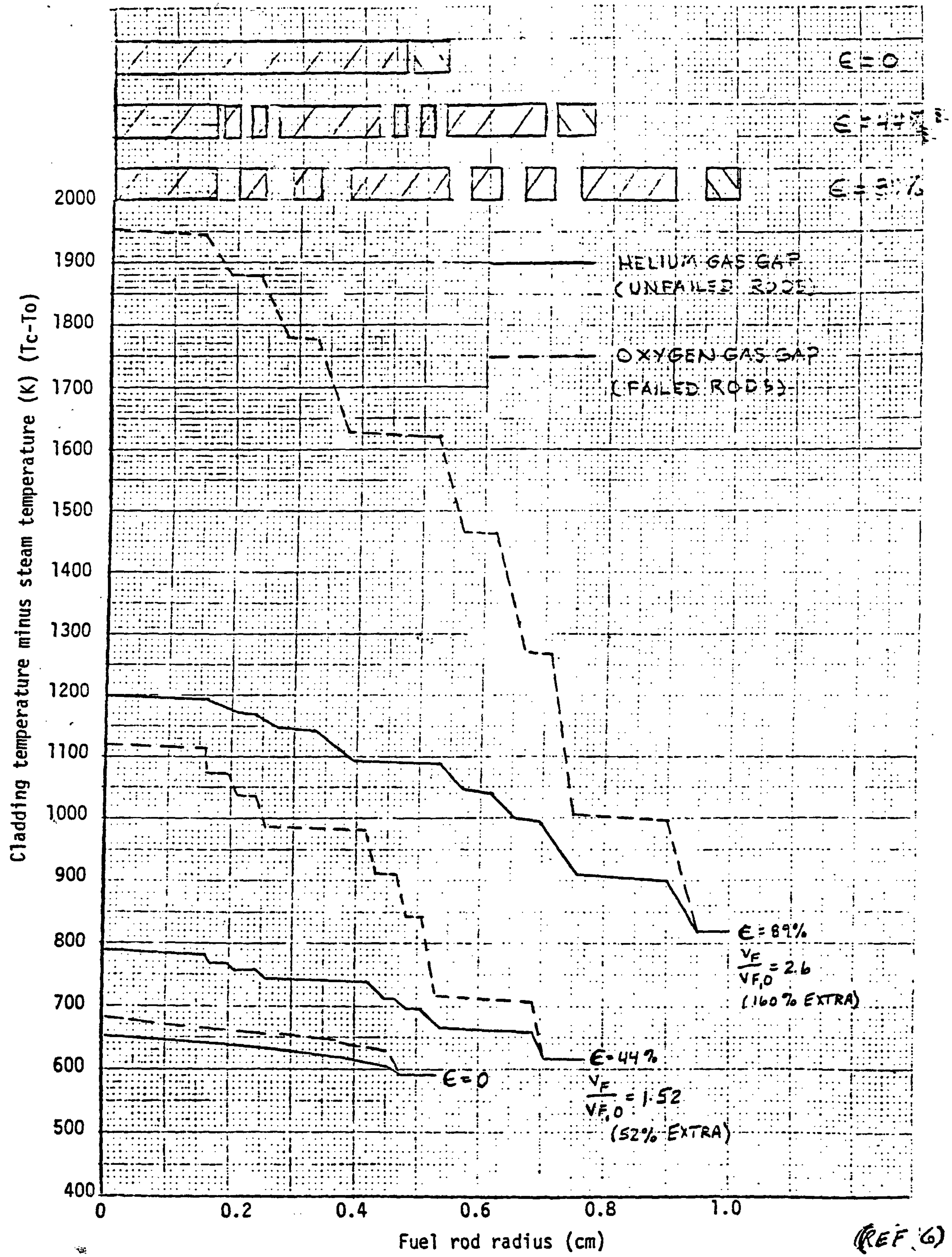
NUREG/CR-0344
ANL-77-31


# DEFORMATION CHARACTERISTICS OF ZIRCALOY CLADDING IN VACUUM AND STEAM UNDER TRANSIENT-HEATING CONDITIONS: SUMMARY REPORT

FIGURE 2


by

H. M. Chung and T. F. Kassner



€=0
€=44%
€=89%
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
HELIUM GAS GAP (UNFAILED RODS)
OXYGEN GAS GAP (FAILED RODS)
€=89%
$\frac{V_F}{V_{F,0}} = 2.6$
(160% EXTRA)
€=44%
$\frac{V_F}{V_{F,0}} = 1.52$
(52% EXTRA)
€=0
Cladding temperature minus steam temperature (K) (Tc-To)
0
0.2
0.4
0.6
0.8
1.0
Fuel rod radius (cm)


(REF 6)

Appendix A

# FR2 In-Pile Tests on LWR Fuel Behavior During the Heatup Phase of a LOCA

Review for Presentation

at the Workshop on Fuel Behavior

June 1980, Karlsruhe

E. Karb, M. Prüßmann, L. Sepold

IT

Kernforschungszentrum Karlsruhe GmbH, Karlsruhe

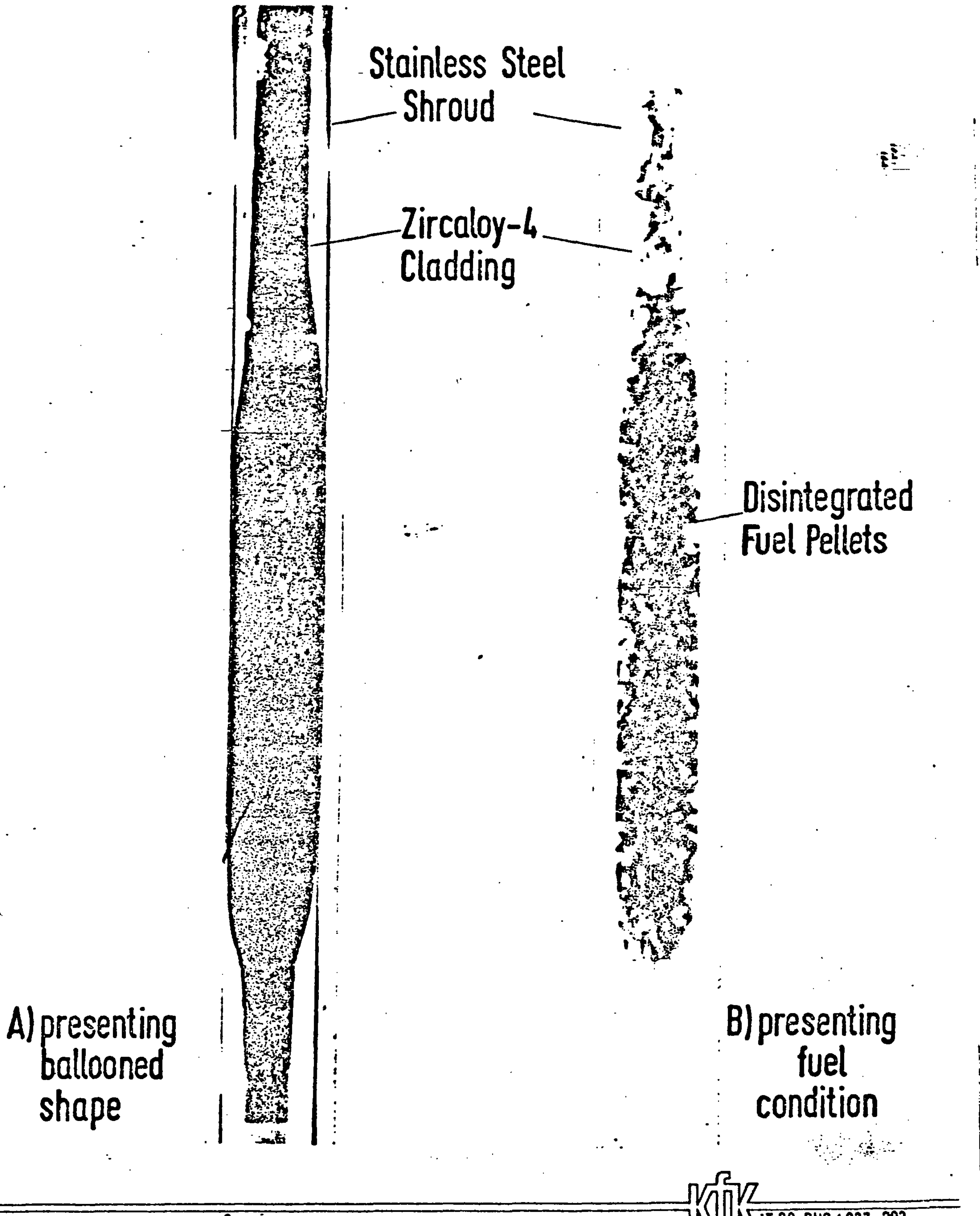
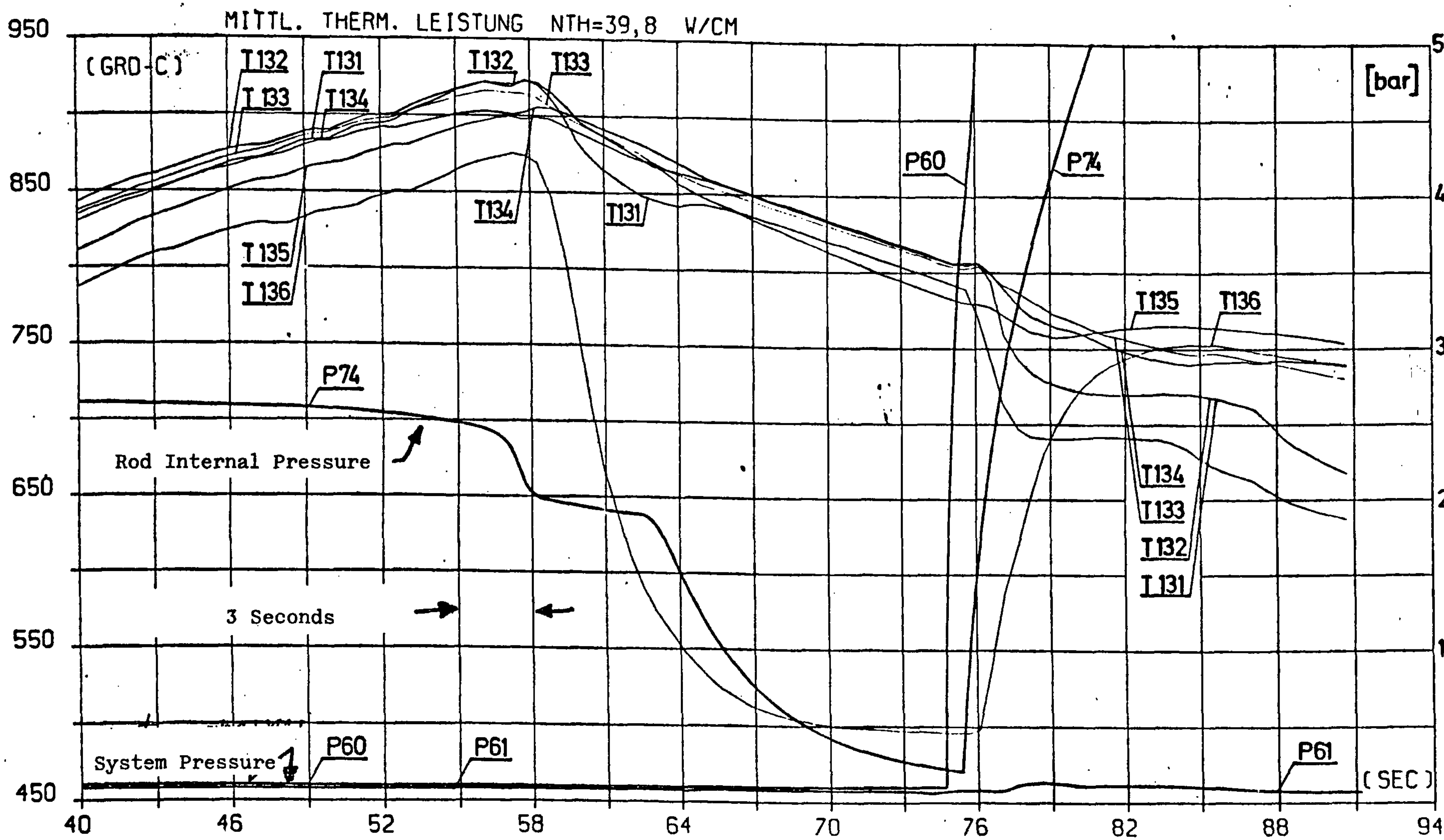



FIGURE A-1

FR2 In-pile Tests E5 Fuel Rod

Posttest Neutron Radiograph

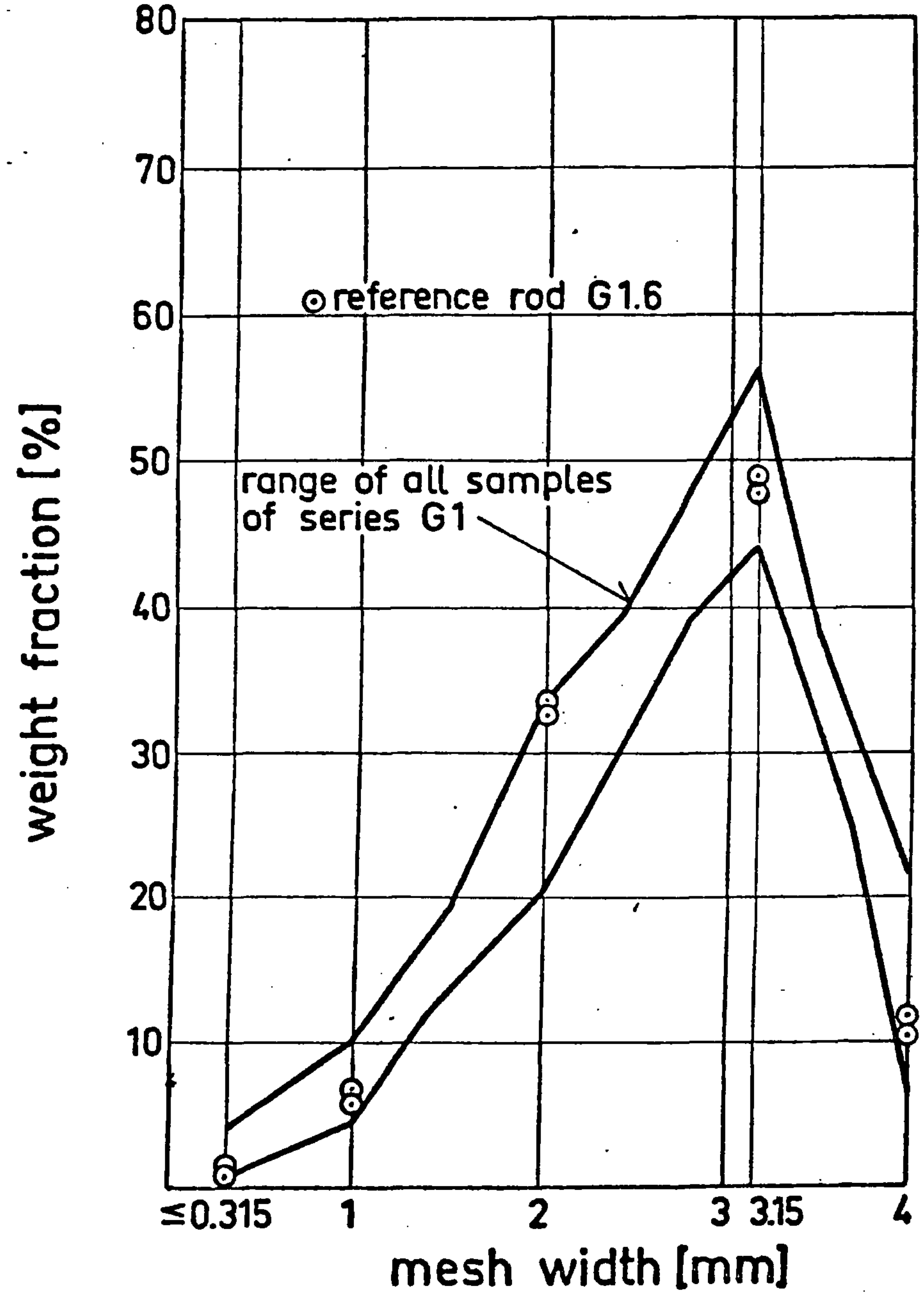
PROJEKT PNS 4237 - VERS. NR. : E 5
VOM 04.03.80 ZEIT 11H03M24S




T131,T132,T133,T134,T135,T136 HUELLROHR-TEMPERATUR

PNS 4237-295

FIGURE A-2




All fuel rods have the same irradiation history
Reference rod G1.6 was not ballooned in a simulated
LOCA but all other G1 series rods were.

KfK IT-80
PNS 4237-301

# FR2 In-Pile Tests: Series G1

## Fuel Particle Size Distribution, Sieve Analyses

Fig. A-3

*Appendix B*

September 29, 1980

Mr. R. E. Tiller, Director
Reactor Operations and Program Division
Idaho Operations Office - DOE
Idaho Falls, ID 83401

STEADY STATE FUEL RUBBLE THERMAL ANALYSIS - HJZ-317-80

Dear Mr. Tiller:

The attached summary documents the results of a steady state thermal analysis of a ballooned PWR fuel rod during a LOCA accident as requested by Dr. M. L. Picklesimer (NRC). The objective of this analysis was to calculate fuel rod temperature distributions in the region where the cladding has ballooned. Fuel redistribution within the ballooned region was considered and a stagnate steam environment and decay heat at 100 s was assumed.

Based on the analysis, the calculated cladding temperature for the worst case (about 90% cladding strain and 160% fuel redistribution) was about 230 K greater than the nominal case of no ballooning or fuel redistribution. Additionally, the maximum fuel temperature within the ballooned region was 1300 K higher than the nominal case. Both temperatures are well below the melting point of the respective materials, indicating that fuel redistribution into a balloon for these conditions will not pose a significant problem during a LOCA accident.

This analysis was intended to provide a "first-cut" evaluation of fuel rod temperatures for a number of assumed conditions. If deemed necessary, a more refined evaluation could be completed that would include a simple computer model and improved estimates of the fuel and gap properties, and fuel distribution within the rod.

Very truly yours,

P. E. MacDonald /for

H. J. Zeile, Manager
Thermal Fuels Behavior Program

TRY/bh

Attachment:
As stated

Appendix B

# STEADY STATE FUEL RUBBLE THERMAL ANALYSIS

T. R. Yackle

I. Objective: Model the temperature distribution in the ballooned region of a fuel rod during the heatup phase of a LOCA. Include in the analysis: (1) the possibility of additional fuel in the ballooned region due to redistribution, and (2) the possibility of cladding failure and a degraded pellet-to-cladding and pellet fragment-to-pellet fragment gap conductance.

II. Model: The fuel rod was modeled by a series of nodes shown in Figure 1. The cracked fuel and additional rubble fuel was modeled as the series of fuel and gap nodes numbered 1 through 7.

III. List of Assumptions:

1. Circumferential heat transfer is small.

2. Axial heat transfer is also small.

3. The fuel pellet has two circumferential cracks. The fuel is cracked into particles that have a dimension of about 1600 μm. This corresponds to measurements of fuel particles made from PBF and KfK (FR-2) tests.

4. Nominal dimensions of a 0.422-inch PWR fuel rod.

5. The cladding surface heat transfer coefficient is 60 $W/m^2$-K. This value is conservative for a stagnant steam environment.

6. An initial rod power prior to reactor scram of 40 kW/m and 3% decay heat at 100 seconds after scram.

7. A flat fuel radial power profile.

8. The fuel rod thermal conductivity is constant at 2.6 W/m·K.

9. The gas thermal conductivity is constant and selected at an average rod temperature of 1500 K.

10. Radiation between fuel particles is small.

IV. Fuel and Gas Properties: The fuel and gas properties are based on MATPRO, Version 11, NUREG/CR-0497, TREE-1280, Rev. 1.

1. The fuel conductivity was assumed to be 2.6 W/mK which is conservative for temperatures about 1850 K.

2. The conductivity of the gas within the unfailed rods was assumed to be 0.45 W/m·K at an average rod temperature of 1500 K as shown in Figure 2.

3. The conductivity of the gas within the failed rod was assumed to be represented by oxygen as shown in Figure 3. A value of 0.1 W/mK at an average rod temperature of 1500 K was selected.

V. Power Generation: An initial peak rod power of 40 kW/m was assumed and the analysis completed for 100 seconds after reactor scram. Power generation at this time is 3% of the original power as shown in the Figure 4 ANS curve.

VI. Fuel Redistribution: The amount of fuel redistribution has been determined from results of the PBF LOC-3 and LOC-5 tests. The degree of redistribution was evaluated by measurements of the fission product decay along the length of the fuel rod. An example of the normalized decay of two fission products within Rod 04 of Test LOC-3 is provided in Figure 5. The decay curves indicate a 30 to 50% fuel redistributed into the ballooned region.

The percent fuel redistribution in the ballooned region of all the Test LOC-3 and LOC-5 rods is compared with the percent cladding volume increase in Figure 6. The uncertainty of the fuel redistribution for each rod is a result of differences in the measurements of the decay of the two fission products. The choice of the cesium fission product as an indicator of fuel movement may be misleading due to cesium volatility and probable movement within the gas of the rod. However, the use of cesium would be conservative as it would likely indicate more fuel relocation than expected. A line was fit through the data that represents the average fuel redistribution compared with the cladding volume increase. A more accurate representation of this line fit, based on additional analyses, is recommended for future effort.

The calculated degree of fuel relocation for a fuel rod with 44 and 89% cladding strain is 52 and 160%, respectively.

VII. Analyses Results: The calculated temperature profiles of a fuel rod with 0, 44, and 89% cladding strains are provided for a number of fuel rod conditions in Figures 7 through 9. In each figure, the gas gap conductivity was assumed to be that of: (1) helium (the upper limit of conductivity of an unfailed rod) and (2) oxygen (the lower limit of conductivity of a failed rod). The temperatures presented in Figure 7 were calculated for a fuel rod with 0, 44, and 89% strain and no fuel relocation or additional fuel redistribution into the balloon. The cladding and fuel were calculated to cool as ballooning occurred and temperatures were relatively low. The temperatures presented in Figure 8 were calculated for a fuel rod with cladding strain and fuel relocation, but no additional fuel redistribution into the balloon. The cladding was again calculated to cool as ballooning occurred. The maximum fuel centerline temperature was only 200 K larger than the fuel temperature of the nominal case with no ballooning. The temperatures presented in Figure 9 were calulated for a fuel rod with cladding strain, fuel relocation, and fuel redistribution into the ballooned region. The cladding temperature of the worst case (89% strain) was calculated to be about 230 K greater than the nominal case. The maximum fuel temperature within the ballooned region was 1300 K larger than the nominal case (no rod deformation). The calculated temperatures are well below the melting point of the respective materials, indicating that fuel redistribution into the balloon for these conditions will not pose a significant problem.

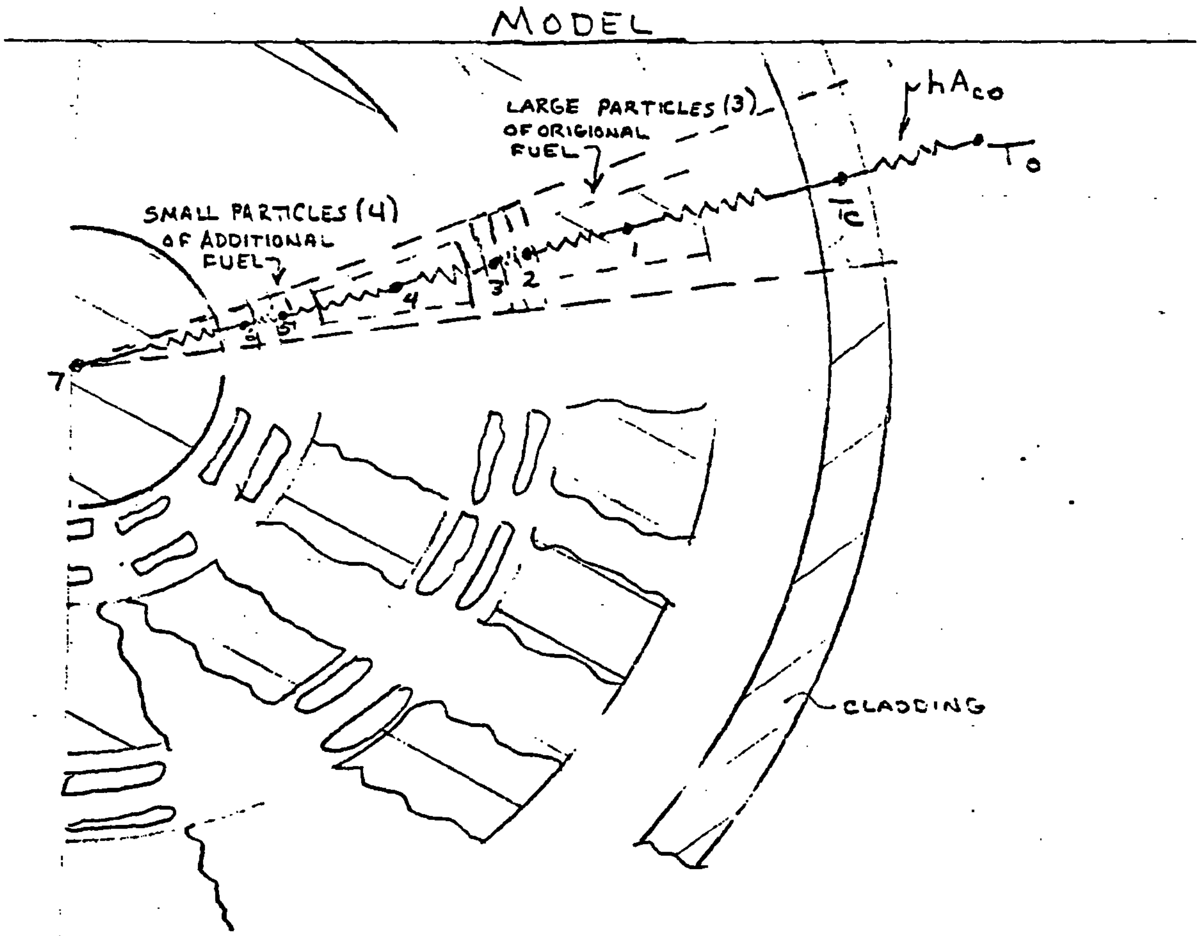



Figure 1. Steady state fuel rubble thermal analyses.

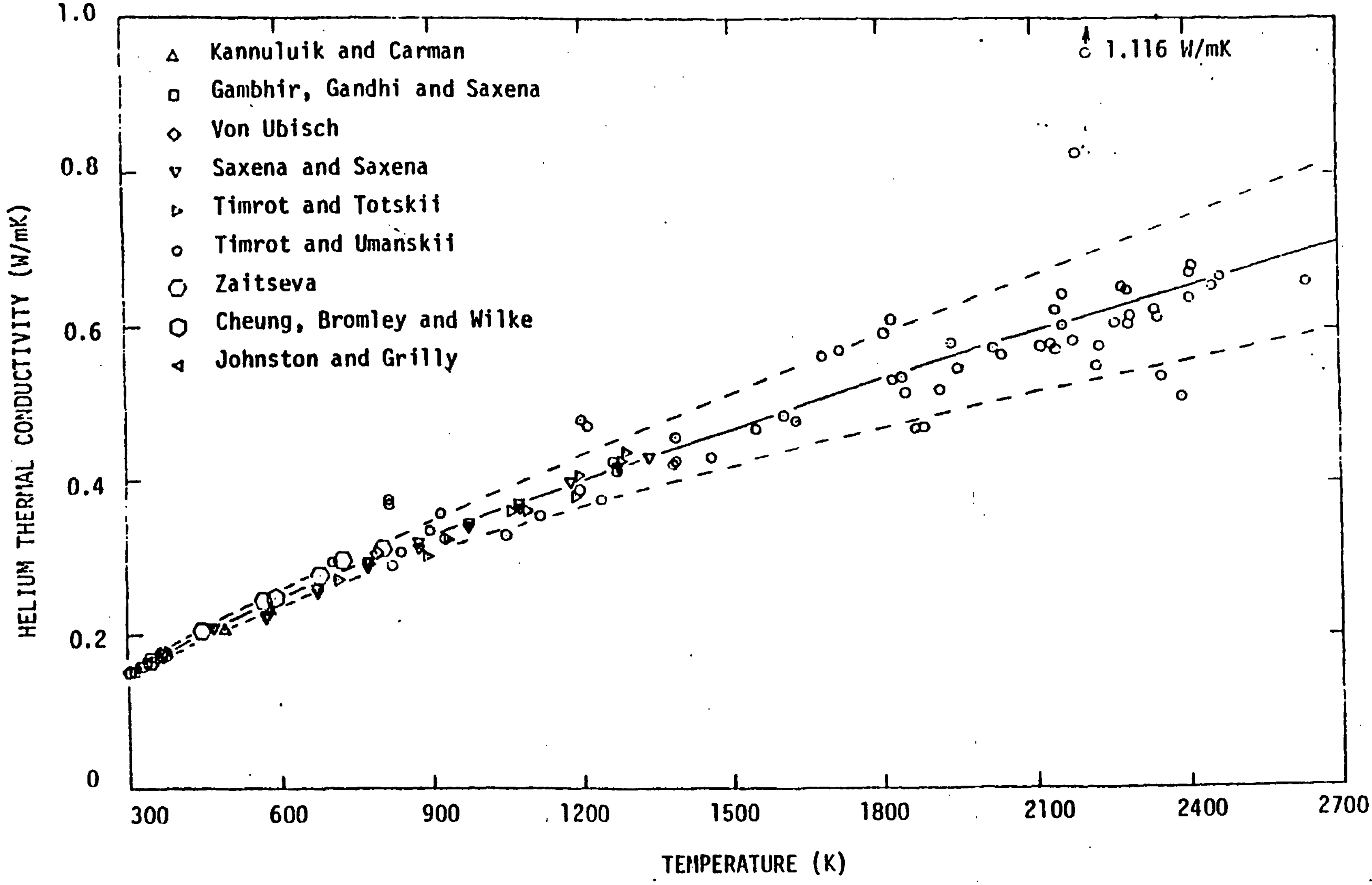



Figure 2. Thermal conductivity of helium as a function of temperature.

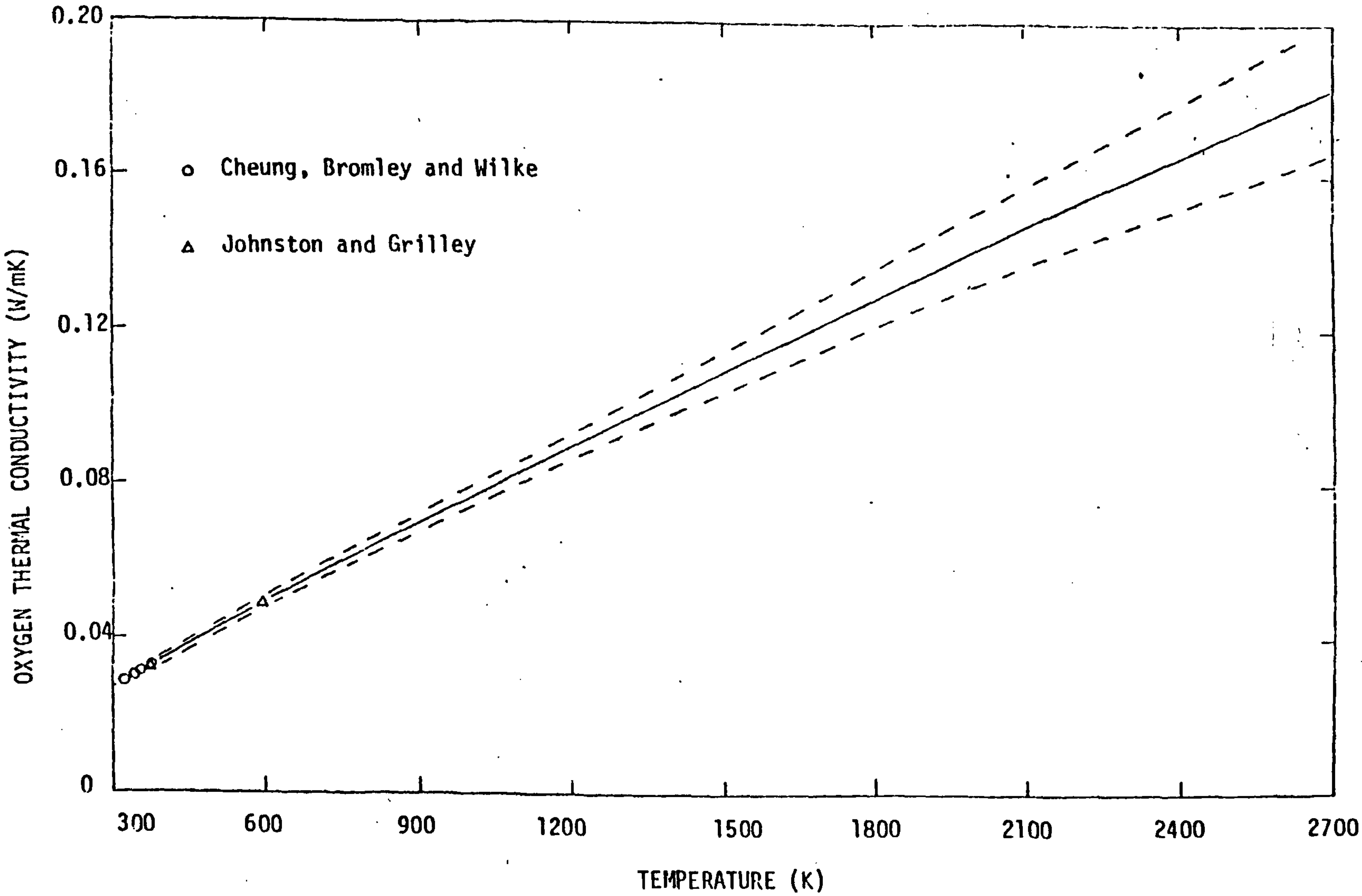



Figure 3. Thermal conductivity of oxygen as a function of temperature.

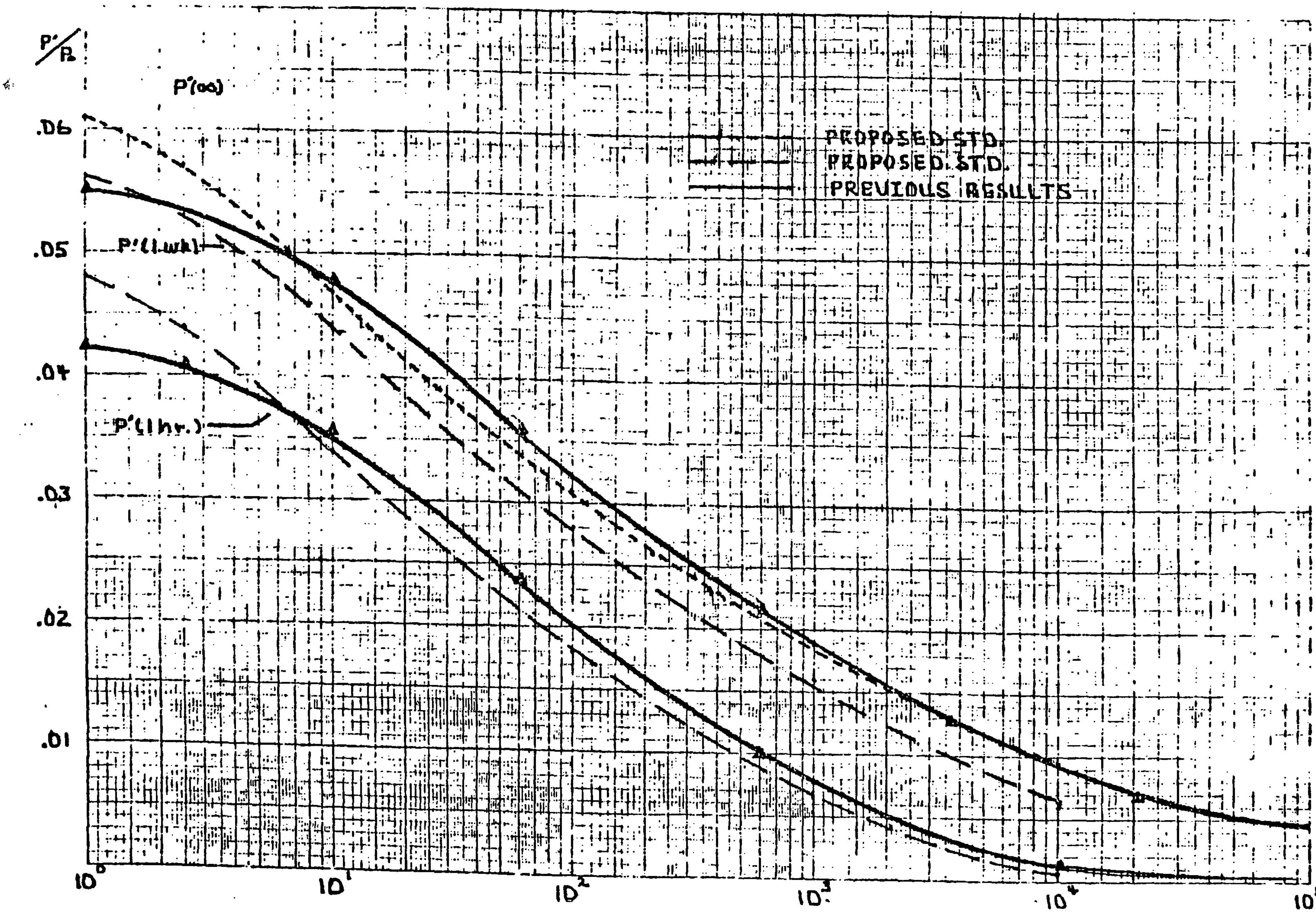



Figure 4. ANS decay curve.

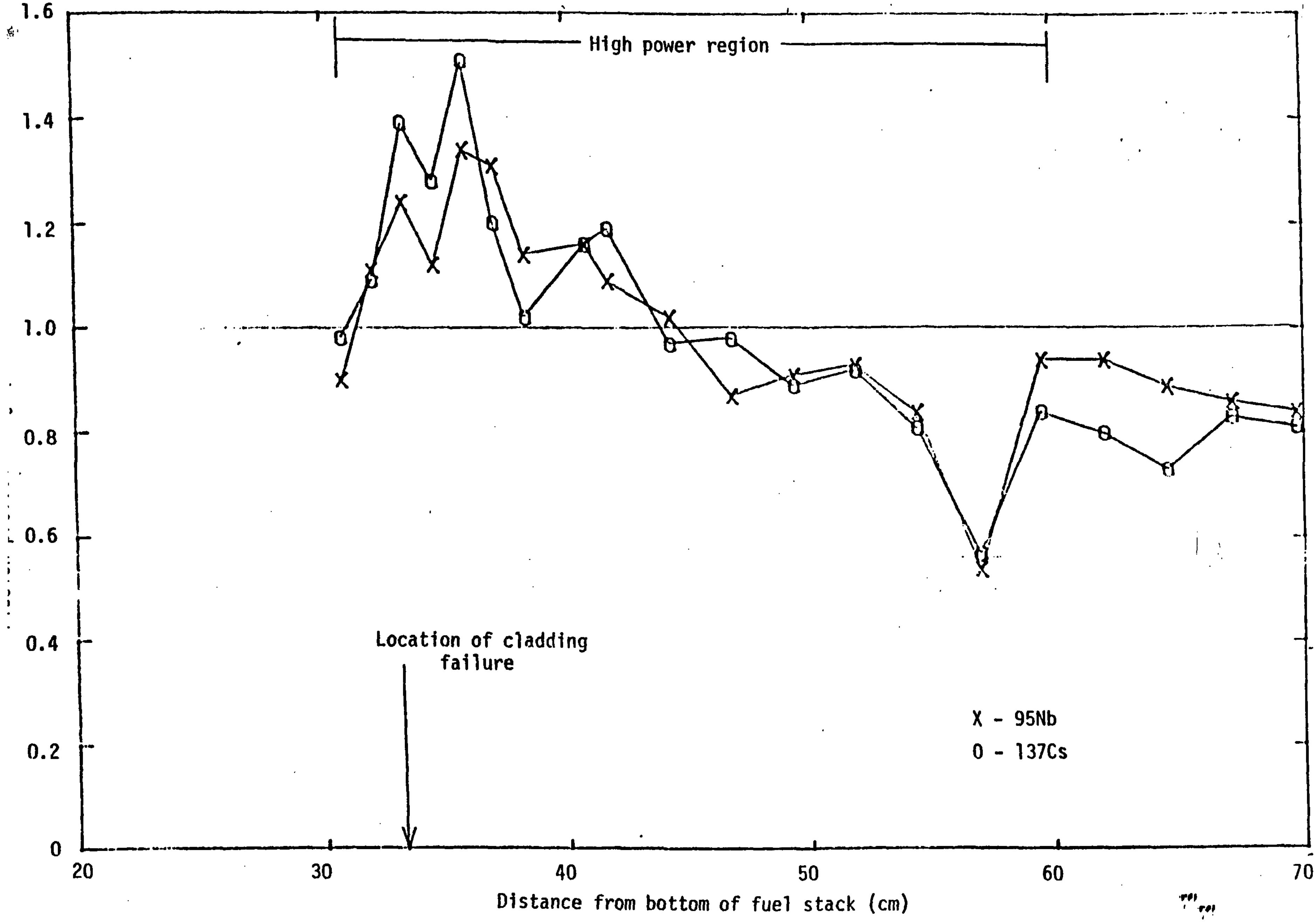



Figure 5. Axial profile of fission product decay curve for LOC-3, Rod 04.

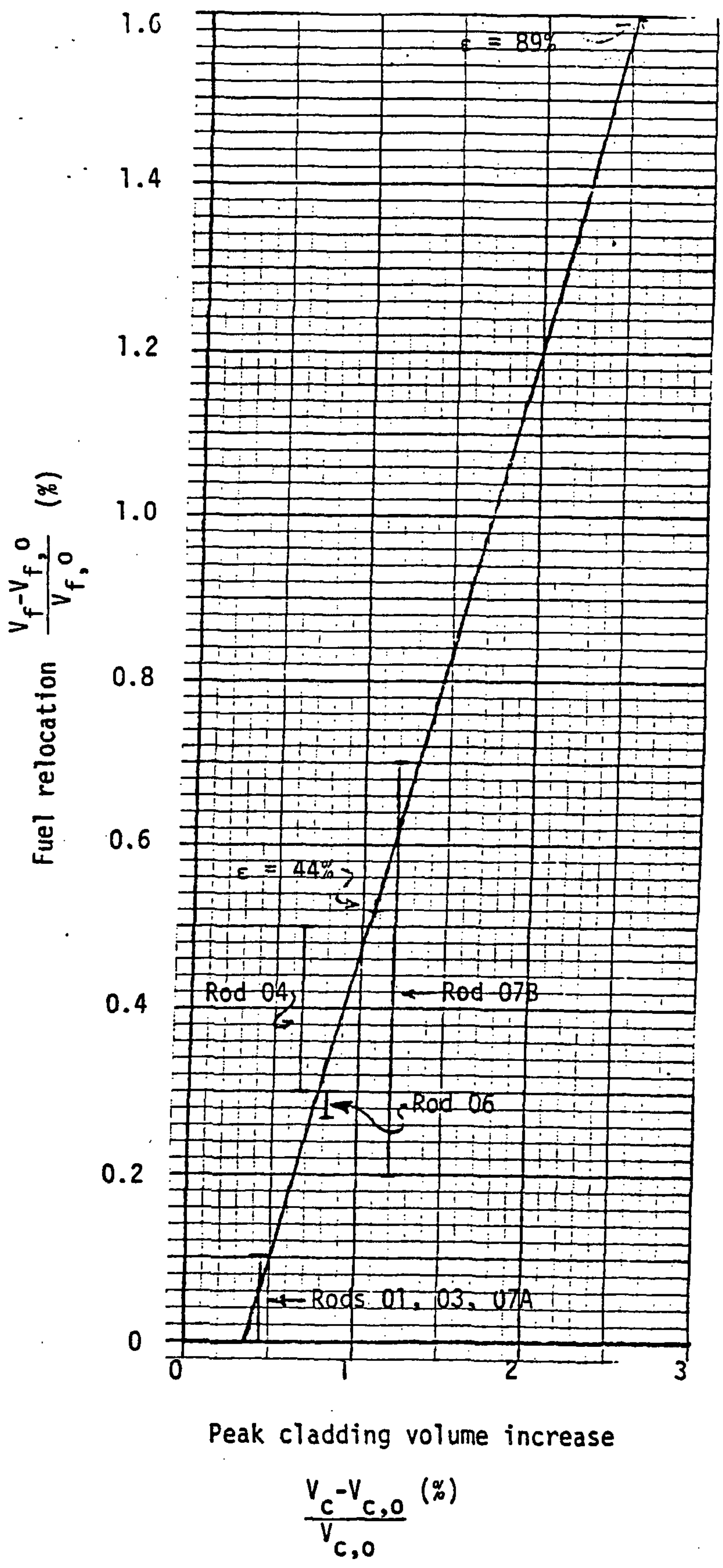



Figure 6. Correlation of fuel relocation to volume increase of ballooned cladding.

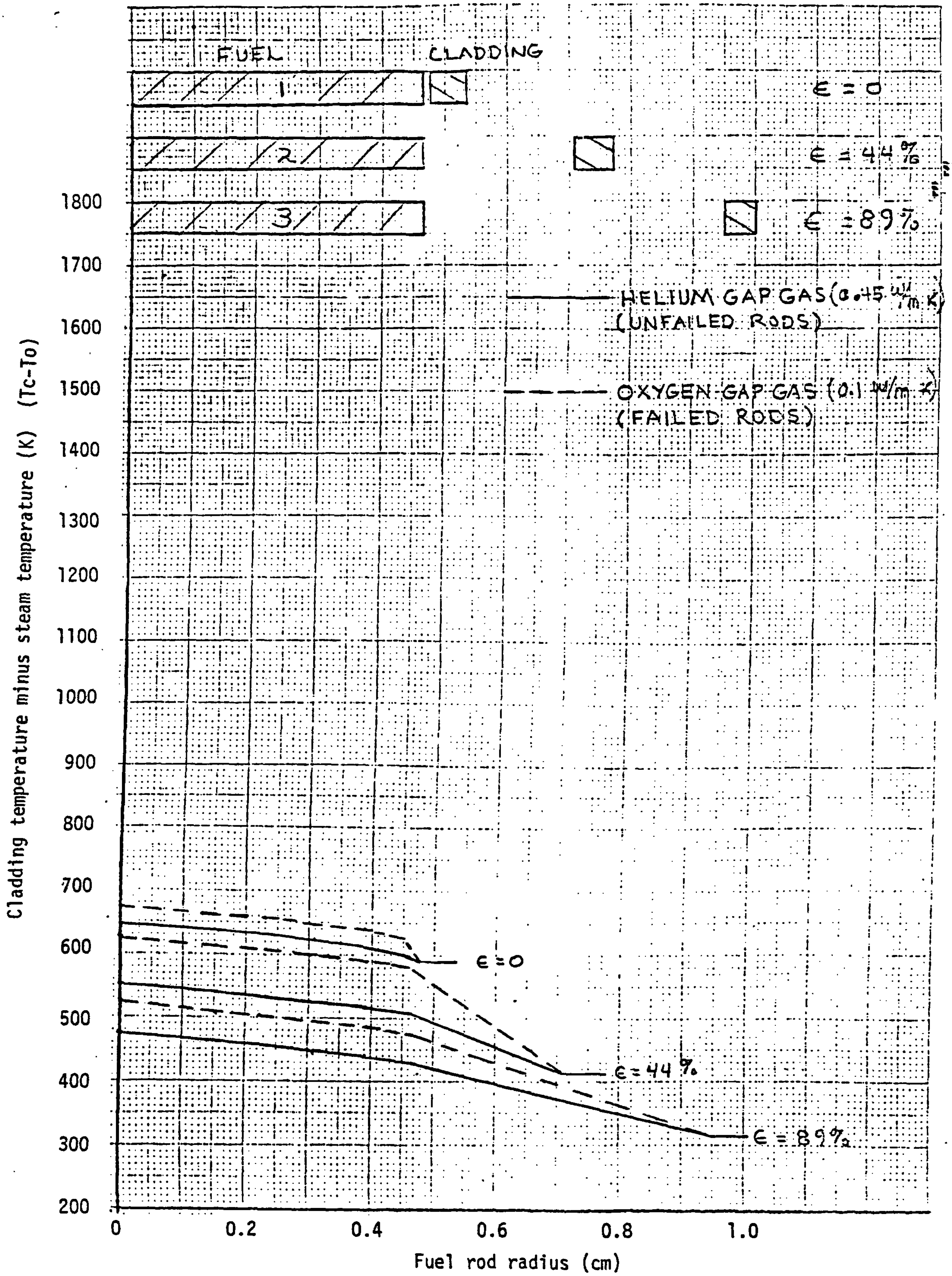



Figure 7. Fuel rod temperatures with 0, 44, and 89% cladding strain and no fuel relocation or redistribution.

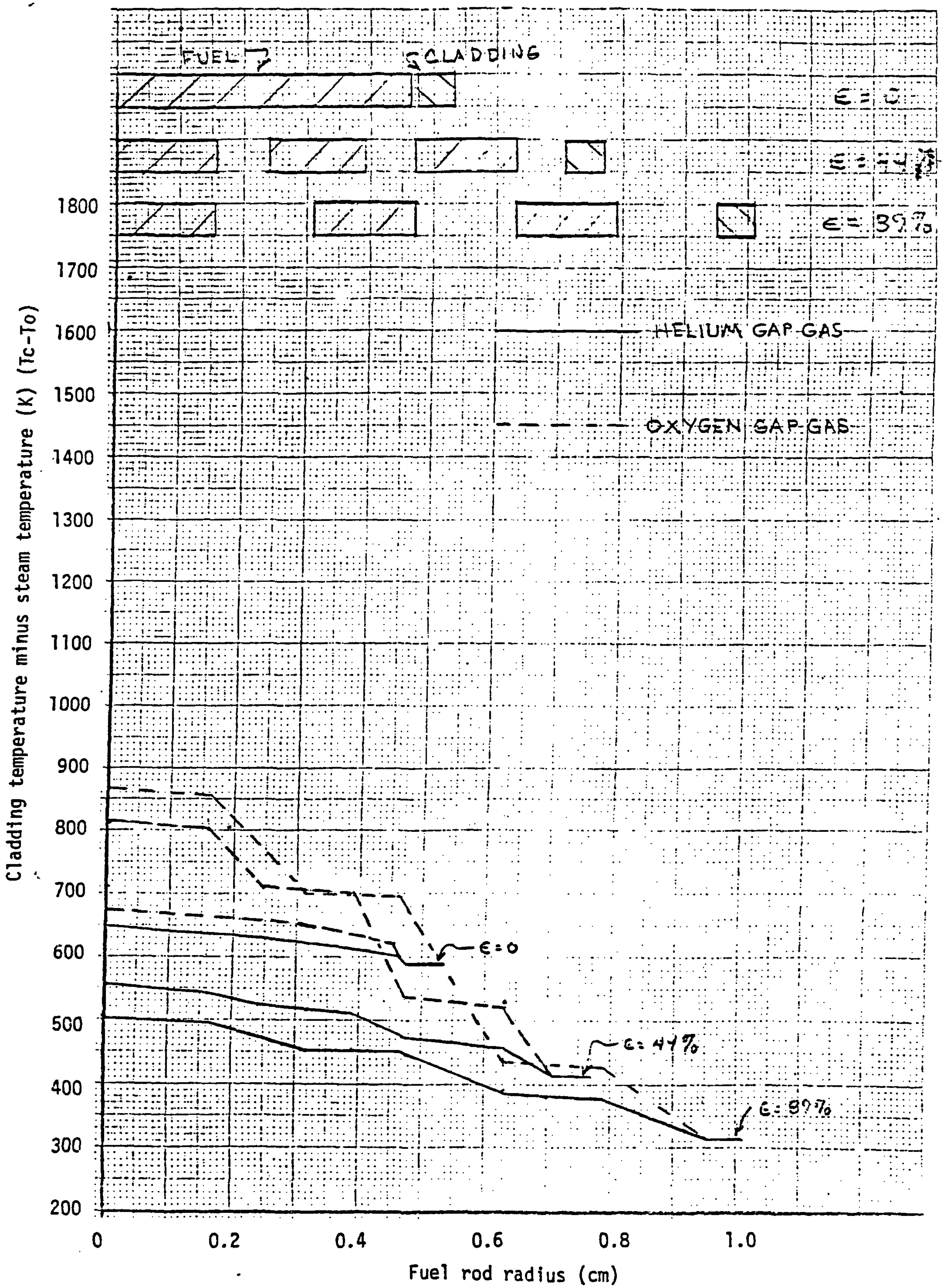



Figure 8. Fuel rod temperatures with 0, 44, and 89% cladding strain and

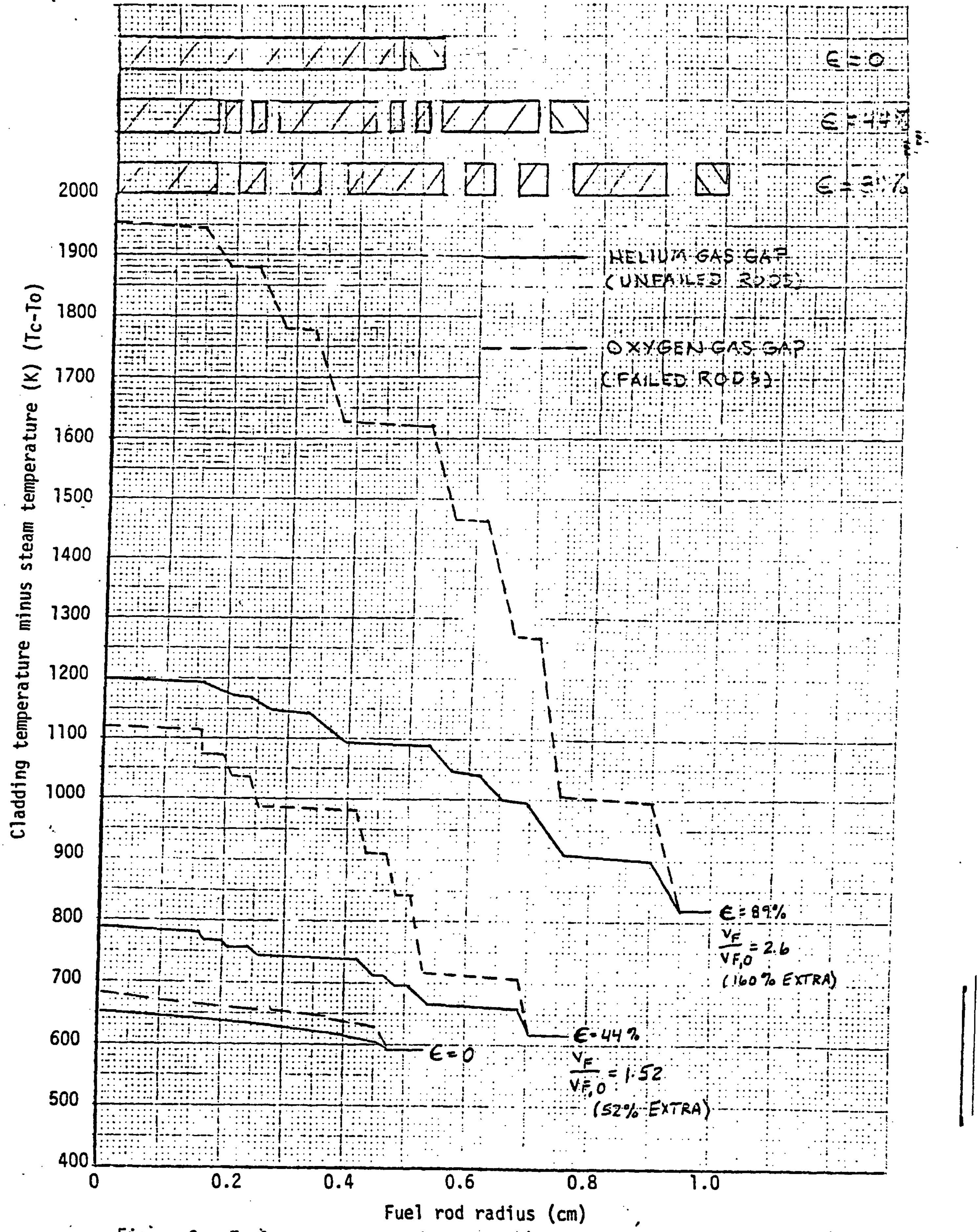



Figure 9. Fuel rod temperatures with 0, 44, and 89% cladding strain, fuel